



# Environmental assessment of CCHP (combined cooling heating and power) systems based on biomass combustion in comparison to conventional generation



Daniel Maraver<sup>a,\*</sup>, Ana Sin<sup>a,1</sup>, Fernando Sebastián<sup>a,1</sup>, Javier Royo<sup>b,2</sup>

<sup>a</sup> Natural Resources Area, Research Centre for Energy Resources and Consumption, C/Mariano Esquillor Gómez, 50.018 Zaragoza, Spain

<sup>b</sup> Department of Mechanical Engineering, University of Zaragoza, C/María de Luna, 50.018 Zaragoza, Spain

## ARTICLE INFO

### Article history:

Received 31 August 2012

Received in revised form

1 February 2013

Accepted 2 February 2013

Available online 9 March 2013

### Keywords:

Biomass

Combined cooling heating and power (CCHP)

Trigeneration

Life cycle assessment (LCA)

## ABSTRACT

Biomass CCHP (combined cooling heating and power) systems based on biomass combustion have already demonstrated their benefits in some operating conditions. However, their environmental and energy performance might not always be better than that of conventional stand-alone generation systems. In order to assess the possible benefits, these plants are evaluated by means of Life Cycle Assessment (LCA) methodology to provide some guidelines regarding their environmental feasibility. A thermodynamic model, which considers the integration of different sizes of cogeneration and cooling units, was developed to contribute to properly defining the life cycle inventory stage. Moreover, the model outputs were used to develop a primary energy savings ratio (PESR) analysis and compare its results with those of the LCA.

The LCA results show that, whereas small plant cooling-to-heating ratios cause CCHP plants based on biomass combustion to be environmentally feasible (they imply environmental benefits compared to conventional average stand-alone generation), high plant cooling-to-heating ratios in fact cause them to be environmentally unfeasible. Results also allow us to state that the use of the PESR by itself might not be adequate to assess the steady-state performance of this type of plant because, in some circumstances, it might limit the plant's feasibility when environmental benefits could still be achieved.

© 2013 Elsevier Ltd. All rights reserved.

## 1. Introduction and objectives

While the energy sector has increasingly focused on issues concerning energy saving by the implementation of more and more efficient systems, both from the technical and the regulatory point of view [1], the need for renewable energy generation has also increased, as ambitious energy policies such as the EU's 20% renewable energy target by 2020 [2] are being put into effect. Based on these premises, renewable combined generation, such as cogeneration (CHP – combined heating and power) or trigeneration (CCHP – combined cooling, heating and power), has become an even more attractive energy alternative, particularly on a medium- and small-scale basis (below 1 or 2 MW<sub>e</sub>).

Two main aspects are behind this assertion. On the one hand, renewable combined generation systems lead to better global

efficiencies in comparison to stand-alone green generation in large power plants, which makes it possible to achieve primary energy savings (PES), emissions reduction and enhancement of the supply network's reliability [3–5]. On the other hand, the use of a renewable source reduces the environmental impact of energy generation and implies an improvement in other socioeconomic areas, such as the sustainability of rural communities, or fuel poverty [6].

Hence, remarkable R + D efforts and advances supported by the EU are being made in renewable CHP and CCHP installations [7,8], and specifically in bio-fuelled installations, since renewable CHP and CCHP are broadly identified as among the alternatives that can meet and solve energy-related problems and the induced environment issues [9–11]. However, the actual achievable benefits of these systems (regarding both energy-related savings and environmental issues) might vary depending on the plant operation, its nominal loads (heating and cooling) and the technologies involved, so it is necessary to assess every plant configuration in depth to verify if it entails significant improvements compared with conventional generation, i.e., heating, cooling and power generation with fossil fuel boilers, compression chillers and large power plants, the technologies that will certainly be replaced by renewable CCHP.

\* Corresponding author. Tel.: +34 976762582; fax: +34 976732078.

E-mail addresses: [dmaraver@fcirce.es](mailto:dmaraver@fcirce.es), [dmaraver@unizar.es](mailto:dmaraver@unizar.es) (D. Maraver), [anasin@unizar.es](mailto:anasin@unizar.es) (A. Sin), [fersebas@unizar.es](mailto:fersebas@unizar.es) (F. Sebastián), [fjroyo@unizar.es](mailto:fjroyo@unizar.es) (J. Royo).

<sup>1</sup> Tel.: +34 976762582; fax: +34 976732078.

<sup>2</sup> Tel.: +34 976762568; fax: +34 976732078.

Based on the main conclusions of previous works by Angrisani et al. [12], Chicco et al. [13] and Maraver et al. [14], the energy feasibility of CCHP, in terms of primary energy savings in comparison to stand-alone generation, is limited by the technologies involved in each installation and by the cooling-to-heating ratio finally implemented. On the other hand, when the environmental point of view is specifically analysed, many authors have dealt with the evaluation of combined generation systems through Life Cycle Assessment (LCA) tools. Pehnt et al. [15] assessed the environmental impact of natural gas fuelled CCHP and CHP plants in comparison to conventional generation, while Carvalho et al. [16] and Jing et al. [17] focused on the optimization of trigeneration and cogeneration systems based on LCA. Other authors have concentrated on renewable systems but they have not compared the results with those from conventional systems: Pehnt et al. [18] made comparisons between renewable energy systems (power, heating and CHP); Staffell et al. [19] and Jing et al. [9] studied the impact of fuel cell CHP and solar CCHP respectively; and Caserini et al. [20], Kimming et al. [21] and Buonocore et al. [22] studied different alternatives for bio-fuelled CHP systems. Finally, Chevalier et al. [23] analysed bio-fuelled CCHP in comparison to conventional generation, but only for a specific (from the technology and plant size point of view) biogas plant. In summary, there is still a gap with respect to the environmental assessment of trigeneration systems based on biomass combustion and the evaluation of the conditions which would reliably lead to their environmental feasibility compared to conventional systems. This assessment might be very important to understand the specific design conditions that would actually entail environmental benefits. This type of analysis completes the thinking of previous works, since the promising performance of trigeneration depends closely upon its design and operation mode when all the possible perspectives, energy, exergy, economic and environmental performance [13,24,25], are taken collectively into account. In addition, on some occasions, the achievement of environmental benefits with trigeneration plants based on biomass combustion might be presupposed, rather than determined, and the results presented in this work allow us to state that this should not always be accepted as a valid hypothesis.

To assess the environmental performance of bio-fuelled trigeneration plants in comparison to the current average stand-alone energy generation in Europe, the LCA methodology has been used, considering the same framework as that developed in previous works [14] (described in the following epigraph) to attain comparable results. The aim of the work presented in this paper is to assess and quantify the environmental feasibility limits of bio-fuelled CCHP plants in comparison to stand-alone generation, with regard to the possible CHP and thermally-activated cooling (TAC) units involved in these systems and the different cooling-to-heating ratios achieved.

In combination with the LCA methodology, the Primary Energy Saving Ratio (PESR) was also analysed, since it is considered by European policies to support efficient plants [26]. Comparison between the environmental results and the primary energy savings results is useful to assess when the former are in consonance with the latter or vice versa.

## 2. Methodology

### 2.1. Comparison framework

The first step in evaluating and comparing the environmental performance of bio-fuelled CCHP systems and conventional generation is to establish an appropriate comparison framework. Only if this is significant and representative can significant conclusions be attained when analysing the results obtained from the assessment or the comparison.

Fig. 1 shows schematically how the comparison has been established. The bio-fuelled trigeneration plant consumes biomass (wood chips,  $\dot{F}$ ) to generate power ( $\dot{W}$ ), cooling ( $\dot{Q}_{cooling}$ ) and heating ( $\dot{Q}_{heating}$ ). This scheme is compared to the conventional scenario in which the same energy products would be generated in average stand-alone plants: a fossil fuel boiler ( $\dot{Q}_{heating}$ ), a compression chiller activated by an average electricity-mix ( $\dot{Q}_{cooling}$ ) and a reference power plant ( $\dot{W}$ ).

### 2.2. Life cycle assessment (LCA)

LCAs were undertaken considering the ISO 14040 standards [27,28] and the methodological issues regarding energy systems, and were performed using the SimaPro 7.3 software package [29] and the Ecoinvent database [30]. The environmental interventions were categorized and weighted according to the Eco-Indicator 99, IMPACT 2002+ and ReCiPe [31–33] impact evaluation methods. These three methods were used due to the possibility of obtaining weighted impact results, which makes it possible to aggregate the impact score of every category to obtain a single result. This will be of great interest when comparing the environmental results with those from the energy efficiency analysis. Furthermore, the use of several impact assessment methods aims to reduce the possible subjectivity of the LCA methodology.

The following life cycle stages of the different subsystems (Fig. 1) involved in the analysis were taken into account. On the one hand, the life cycle inventory of the bio-fuelled CCHP plant considers the wood procurement, the wood chip production requirements, their transport to the plant, the combustion process, the ash disposal and finally the infrastructure and dismantling of the boiler, the prime mover and the chiller [34,35]. On the other hand, the life cycle inventory of the stand-alone reference system considers the individual generation of heating, electricity and cooling. Firstly, the heating generation includes the fuel procurement, obtaining it at the plant from the natural gas high pressure network, the infrastructure and the dismantling of the (boiler), the combustion process and the electricity required for operation [36]. Secondly, the power generation considers the most recent available energy statistics and the corresponding databases [37] to obtain the current EU-27 mix scenario, which takes into account the average electricity production in Europe, the transmission network infrastructure and dismantling, as well as the direct emissions and the electricity losses involved. Hence, according to the Europe Annual Energy Report [38], the mix considered is based on the combined power generation from different sources [36]: coal and other solid fuels, oil, natural gas, hydropower, nuclear, photovoltaic, wind power and biomass. Finally, the cooling generation considers the infrastructure and dismantling of the chiller (according to the available databases [35]) and the electricity required for its operation (also coming from the EU-27 mix).

For every system assessed, 1 h of operation was defined as the functional unit. The impact results were obtained by weighting

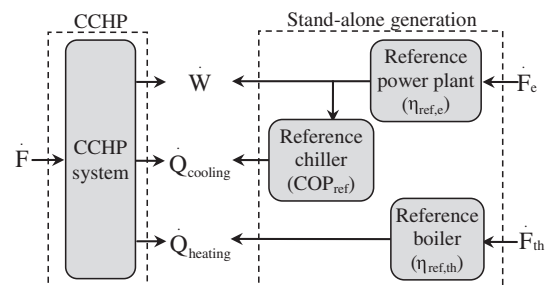


Fig. 1. Comparison framework.

every category considered by the evaluation method (Eco-Indicator 99, IMPACT 2002+ and ReCiPe) and the difference between CCHP and conventional generation impacts was estimated as:

$$\Delta \text{IMPACT} = \frac{\text{IMPACT}^{\text{stand-alone}} - \text{IMPACT}^{\text{CCHP}}}{\text{IMPACT}^{\text{stand-alone}}} \quad (1)$$

### 2.3. Parameter analysis

As was previously mentioned, the Primary Energy Saving Ratio (PESR) was also analysed to compare both generation alternatives and to determine if regulatory support for efficient plants, normally based on this parameter [26], agreed with environmental results. This ratio usually takes into account the steady-state performance and does not consider partial load operation or plant management [39]. It is generally used to compare multiproduct systems against reference plants with the same energy products ( $W$ ,  $\dot{Q}_{\text{cooling}}$  and  $\dot{Q}_{\text{heating}}$  in Fig. 1). Actually, PESR is the amount of saved energy, represented by the difference between two terms: the fuel consumed in a stand-alone system and in a CCHP scheme ( $F_e + F_{\text{th}}$  and  $\dot{F}$ , respectively, in Fig. 1) [3]. Therefore, it can be expressed as

$$\text{PESR} = 1 - \frac{\dot{F}}{\frac{W}{\eta_{\text{ref},e}} + \frac{\dot{Q}_{\text{heating}}}{\eta_{\text{ref},th}} + \frac{\dot{Q}_{\text{cooling}}}{\eta_{\text{ref},e} \cdot \text{COP}_{\text{ref}}}} \quad (2)$$

The appropriate selection of efficiency values for the reference subsystems ( $\eta_{\text{ref},e}$ ,  $\eta_{\text{ref},th}$  and  $\text{COP}_{\text{ref}}$ ) is decisive to attain results that are representative enough. Nevertheless, since the PESR is considered by EU policies to support efficient plants, unanimous reference values are depicted by the Commission Implementing Decision of 19 December 2011 [40]. These values depend on the primary energy source used in the analysed CCHP plant.

Therefore, in this case, the reference power plant's net electric efficiency ( $\eta_{\text{ref},e}$ ) finally selected for the comparison is 33%, which actually corresponds to the case of a representative wood-fuelled steam power plant. For the thermal generation,  $\eta_{\text{ref},th}$  has been set to 86%, which corresponds to a reference wood boiler. Finally, due to the lack of a reference system for the cooling generation, a high performance vapour-compression chiller ( $\text{COP}_{\text{ref}} = 4$ ), which consumes electricity from the reference power plant, has been selected.

Hence, the comparison framework of the parameter analysis depicted by the EU policy is based on assessing the energy efficiency performance of the assessed system in comparison to a hypothetical scenario in which the same type of biomass as that used in the CCHP plant would separately fuel a biomass power plant to produce electricity and cooling (through a vapour-compression chiller), and a biomass boiler to produce heat. Both the power plant and the boiler would work in the conditions given by their reference value efficiencies.

## 3. CCHP system description

The appropriate technologies for integration in medium- and small-scale bio-fuelled CCHP systems are the organic Rankine cycle and the Stirling engine as the cogeneration units, and the absorption and the adsorption chillers as the cooling generators. These technologies, as well as a general thermodynamic model used to obtain the environmental and the parameter assessment inputs, are presented in this epigraph.

### 3.1. Subsystem integration

Organic Rankine cycles (ORC) and Stirling engines (SE) are two promising and innovative technologies which are of great interest

for biomass CHP plants up to 2 MW<sub>e</sub> [41]. A summary of the average performance characteristics of both prime movers is shown in Table 1.

ORC units can be divided into two main groups. On the one hand, the medium to large-scale modules (>200 kW<sub>e</sub>) operate with working fluids with higher evaporation temperatures (n-pentane, toluene or siloxanes), which entail both better efficiencies (15–23%) and also the possibility of condensing at temperatures that enable the use of rejected heat (>60 °C). On the other hand, small units, up to 200 kW<sub>e</sub> (or even 250 kW<sub>e</sub> in some modules), usually use low boiling point hydrocarbons (R134a, R245fa, R152a) as working fluids, which entail lower efficiencies (8–15%) and lower heat sink temperatures (~25 °C), which limit the subsequent direct use of the rejected heat.

Absorption and adsorption chillers are thermally driven technologies (TAC, thermally activated chillers) which are widely applied in existing CCHP systems, replacing conventional vapour-compression chillers with significant electric consumption. Table 2 summarizes the average characteristics of commercial TAC units.

According to their operation parameters, it is possible to assess the integration of ORC or SE and absorption or adsorption refrigeration technologies in CCHP plants based on biomass combustion. Fig. 2 shows a schematic view of the bio-fuelled CCHP system, representing a general integration of all the possible subsystems.

Depending on the PM heat sink and the chiller heat source temperature, it is possible to take advantage of a cascade utilization of energy, which is the direct coupling of both units. Unfortunately, this direct coupling is not always possible in terms of thermodynamics due to the higher temperature of the cooling unit heat source (typically 60–90 °C) in comparison to the prime mover heat sink. This usually happens in the case of small-scale ORC units (heat sink temperatures between 20 and 35 °C), whereas in ORCs with net power outputs over 200 kW<sub>e</sub>, and in SEs, the heat sink temperature varies from 20 to 35 °C (power generation) to 60–80 °C (CHP). However, it is possible to achieve their integration in CCHP plants. To do so, the prime mover cooling flow must increase its temperature to drive the refrigeration unit and the heating. Such a temperature increase can be achieved by the use of biomass flue gases exhausted from the same burner that also provided the prime mover heat source.

Hence, three main groups of PM and two main groups of TAC units can be combined based on their working principle and operation parameters, which will lead to six different integration possibilities (see Table 3):

- ORC with low temperature working fluids (typically small-scale power range), such as low boiling point hydrocarbons, integrated with adsorption or absorption cooling. Configuration 1 (ORC<sub>lowT</sub> + ADS) and 2 (ORC<sub>lowT</sub> + ABS).
- ORC with high temperature working fluids, such as siloxanes, integrated with adsorption or absorption cooling. Configuration 3 (ORC<sub>highT</sub> + ADS) and 4 (ORC<sub>highT</sub> + ABS).

**Table 1**  
Summary of prime movers' average performance characteristics [14].

| Technology                            | SE                         | ORC                                                   |
|---------------------------------------|----------------------------|-------------------------------------------------------|
| Power range (kW <sub>e</sub> )        | 1–150                      | 3–2000                                                |
| Electric efficiency (%)               | 15–35                      | 8–23                                                  |
| Heat source temperature (°C)          | 650–1100                   | 90–400                                                |
| Cooling temperature (°C) <sup>a</sup> | 20–80                      |                                                       |
| Working fluids                        | Helium, hydrogen, nitrogen | R245fa, R134a, R152a, n-pentane, toluene or siloxanes |

<sup>a</sup> Cooling temperatures vary widely depending on the use mode: CHP or electricity generation only.

**Table 2**  
Characteristics of commercial absorption and adsorption technologies [14].

| Technology                            | Absorption                                |                                   |                          | Adsorption       |               |
|---------------------------------------|-------------------------------------------|-----------------------------------|--------------------------|------------------|---------------|
|                                       | Ammonia–water                             | Water–lithium bromide             |                          | Silica gel–water | Zeolite–water |
|                                       | Single effect                             | Single effect                     | Double effect            |                  |               |
| Cooling capacity (kW <sub>th</sub> )  | 9–3500                                    | 15–7000                           | 230–20,000               | 5–1700           | 3–430         |
| Coefficient of performance (–)        | 0.5–0.7                                   | 0.6–0.75                          | 1.2–1.45                 | 0.56–0.6         | 0.55–0.69     |
| Chilled water temperature (°C)        | (–50)–0 <sup>a</sup><br>6–12 <sup>b</sup> | 5–10                              |                          | 6–12             | 10–15         |
| Heat driving circuit temperature (°C) | 80–115                                    | 80–180<br>Sat. steam<br>(1–3 bar) | <200 Sat. steam (<8 bar) | 32–90            | 45–100        |

<sup>a</sup> Industrial cooling applications.

<sup>b</sup> Air conditioning applications.

- SE integrated with adsorption or absorption cooling. Configuration 5 (SE + ADS) and 6 (SE + ABS).

### 3.2. CCHP model

The thermodynamic model described in this section contributes to properly defining the life cycle inventory stage. Moreover, the model outputs were used to develop a primary energy savings analysis and compare its results with those from the LCA.

Considering the integration of all the subsystems, the relevant plant model can be represented as depicted in Fig. 2 and summarized below.<sup>3</sup>

Biomass ( $\dot{F}$ ) feeds the burner to obtain a certain heat rate from its combustion ( $\dot{Q}_{\text{burner}}$ ), which can be entirely used to drive the PM ( $\dot{Q}_{\text{extra}} = 0$ ;  $\dot{Q}_{\text{burner}} = \dot{Q}_{\text{act,PM}}$ ) if the heat rate rejected from the prime mover ( $\dot{Q}_{\text{rej,PM}}$ ) has a higher temperature than that required by the chiller. In this case, the PM cooling flow can be used to drive the TAC unit to produce  $\dot{Q}_{\text{cooling}}$ . Also, there might be a case when the nominal heat source temperature which activates the TAC is higher than that of the rejected heat. Then, extra heat from the burner would be required to raise the temperature of the PM cooling flow until it can properly drive the chiller within its nominal operation characteristics ( $\dot{Q}_{\text{extra}} \neq 0$ ;  $\dot{Q}_{\text{burner}} > \dot{Q}_{\text{act,PM}}$ ).

The heat rate of the burner can be estimated as

$$\dot{Q}_{\text{burner}} = \dot{F} \cdot \eta_{\text{burner}} \quad (3)$$

where  $\eta_{\text{burner}}$  is the biomass burner thermal efficiency. This heat rate can be split into two terms:

$$\dot{Q}_{\text{burner}} = \dot{Q}_{\text{act,PM}} + \dot{Q}_{\text{extra}} \quad (4)$$

The heat rate supplied to the PM by the flue gases from biomass combustion is estimated, neglecting heat losses, as

$$\dot{Q}_{\text{act,PM}} = \dot{W} + \dot{Q}_{\text{rej,PM}} \quad (5)$$

where  $\dot{Q}_{\text{rej,PM}}$  is the rejected heat rate requirements to ensure the performance of the thermodynamic power cycle and  $\dot{W}$  is the power produced by the prime mover, which can be obtained as

$$\dot{W} = \dot{Q}_{\text{act,PM}} \cdot \eta_{\text{PM}} \quad (6)$$

where  $\eta_{\text{PM}}$  is the electric efficiency of the prime mover.

The heat rate rejected by the PM ( $\dot{Q}_{\text{rej,PM}}$ ) is then split to drive the TAC unit, as described above, and to be used for heating

purposes ( $\dot{Q}_{\text{heating}}$ ). If part of  $\dot{Q}_{\text{rej,PM}}$  is not used to generate cooling nor heating, heat losses ( $\dot{Q}_{\text{loss}}$ ) are also taken into account.

$$\dot{Q}_{\text{rej,PM}} = \dot{Q}_{\text{act,TAT}} + \dot{Q}_{\text{heating}} + \dot{Q}_{\text{loss}} \quad (7)$$

The cooling effect ( $\dot{Q}_{\text{cooling}}$ ) depends on the supplied heat rate source to the chiller ( $\dot{Q}_{\text{act,TAC}}$ ) and its coefficient of performance ( $\text{COP}_{\text{TAC}}$ ):

$$\dot{Q}_{\text{cooling}} = \dot{Q}_{\text{act,TAC}} \cdot \text{COP}_{\text{TAC}} \quad (8)$$

Finally, a so-called cooling factor ( $C$ ) was specifically defined to vary the cooling-to-heating ratio of the system, since the most common operation strategy of CCHP systems is based on following the heating and cooling demands. The cooling factor is defined as:

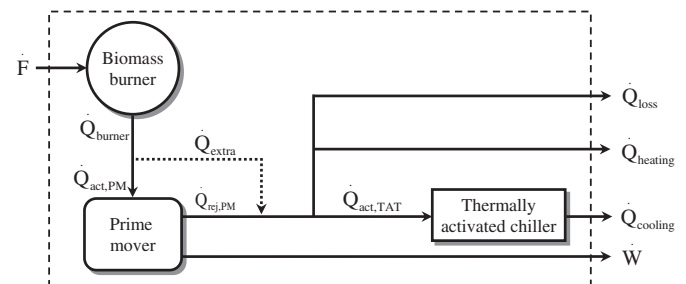
$$C = \frac{\dot{Q}_{\text{cooling}}}{\dot{Q}_{\text{cooling}} + \dot{Q}_{\text{heating}}} \quad (9)$$

According to Eq. (9), low  $C$  values represent high production of heating ( $\dot{Q}_{\text{heating}}$ ) in comparison to cooling ( $\dot{Q}_{\text{cooling}}$ ); hence, a CHP plant is represented by a zero cooling factor. This parameter has been proposed in order to evaluate the environmental impact results in terms of the relation between the amounts of the generated heating and cooling in the CCHP system.

The operation parameters of every subsystem taken into account, based on the data collected in Tables 1 and 2, are presented in Table 4.

## 4. Results and discussion

Differences between the environmental impacts of the assessed CCHP configurations and the reference stand-alone case (see Eq. (1)) have been obtained for different plant cooling factor objectives (see Eq. (9)) by means of the model and the LCA tool. Figs. 3–5 show the LCA results, whereas Fig. 6 represents the energy efficiency



**Fig. 2.** Schematic description of the CCHP model.

<sup>3</sup> All the heat rates and power detailed in the model description are expressed as absolute values.



**Table 3**

Summary of CCHP configurations proposed depending on the technologies involved.

|           |     | Prime movers        |                      |                 |
|-----------|-----|---------------------|----------------------|-----------------|
|           |     | ORC <sub>lowT</sub> | ORC <sub>highT</sub> | SE              |
| TAC units | ADS | Configuration 1     | Configuration 3      | Configuration 5 |
|           | ABS | Configuration 2     | Configuration 4      | Configuration 6 |

results of the CCHP configurations based on biomass combustion compared with the conventional generation systems proposed.

From Figs. 3–5 it can be seen that for every proposed configuration and for all the environmental assessment methods used, all the trigeneration plants producing small cooling loads ( $C < 0.1–0.3$ ) in comparison to heating (which includes all the plants represented by  $C = 0$ , that is, CHP plants), entail environmental impact savings (up to a maximum value of 65%) compared with average conventional generation.

As expected from previous works, a rise in the  $C$  parameter implies a decrease in the environmental impact savings between the CCHP plant and the reference system (average European scenario). This means that the higher the cooling-to-heating generation ratio is, the lower the environmental benefits that will be achieved by the CCHP plant operation. Nevertheless, some of the proposed configurations are more sensitive to a cooling factor variation than others. Configurations 3 and 5, where the rejected heat from the prime mover is directly used ( $T_{ref,PM} \geq T_{act,TAC}$ ), would make it possible to achieve environmental benefits with respect to the reference case even at higher  $C$  values. These configurations make it possible to avoid the extra heat ( $\dot{Q}_{extra}$ ) from the biomass burner achieving the heat source temperature necessary to activate the TAC. Extra heat use required to raise the temperature of the PM cooling flow but afterwards not wholly used for heating or cooling purposes prompts the increment of the negative slopes of the environmental impact reduction and the PESR curves (Configurations 1, 2, 4 and 6), conditioning the  $C$  limit value which makes it possible to achieve environmental benefits in comparison to the reference system.

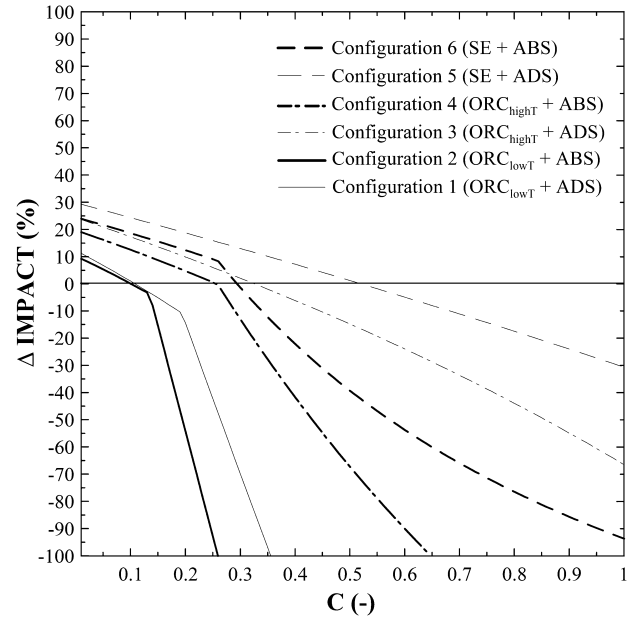
It is also important to note that Configurations 5 and 6, those involving SE, the PM which has the highest electric efficiency of those considered, achieve the best environmental impact performance when the cooling load is relatively low ( $C < 0.3$ ) compared with the heating generated. However, as stated before, the rise in the cooling factor implies that in order to achieve a decrease in environmental impact, the direct coupling of the PM and the TAC units is more important than the high electric efficiency of the PM. So, the rise in  $C$  improves the performance of Configuration 3 (ORC<sub>highT</sub> + ADS) compared with Configuration 6 (SE + ABS), despite the higher efficiency and COP of the SE and the absorption chiller, respectively.

When comparing the results of the environmental and the energy efficiency assessments, it is important to note that, whereas

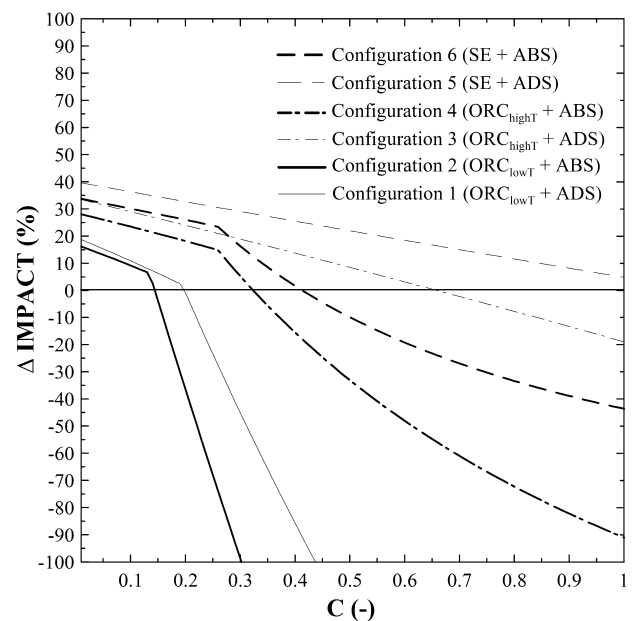
**Table 4**

Input parameters used in the CCHP model.

| Subsystem                        | Parameters                  | Units                  | Value |
|----------------------------------|-----------------------------|------------------------|-------|
| Boiler<br>Power<br>(prime mover) | Efficiency, $\eta_{burner}$ | %                      | 85    |
|                                  | Efficiency, $\eta_{PM}$     | ORC <sub>highT</sub> % | 18    |
|                                  |                             | ORC <sub>lowT</sub> %  | 9.5   |
|                                  |                             | SE %                   | 25    |
| Cooling (TAT)                    | $\Delta T_{ref,PM}$         | °C                     | 20    |
|                                  | Coefficient of performance, | ADS                    | 0.6   |
|                                  | COP <sub>TAT</sub>          | ABS                    | 0.7   |
|                                  | Activation temperature      | ADS                    | 70    |
|                                  | $T_{act,TAT}$               | ABS                    | 90    |

**Fig. 3.** Weighted environmental impact reduction for the comparison framework proposed. Eco-Indicator 99.

some plants might not be considered feasible from the energy efficiency point of view ( $PESR < 0\%$ ), and, hence, by the EU legislation, these installations would still achieve environmental benefits compared with the average European energy scenario (average stand-alone generation). As an example, for configurations integrated by the ORC<sub>lowT</sub>, this difference occurs in the  $C$  ranges 0.05–0.1 (Eco-Indicator 99), 0.05–0.15 (IMPACT 2002+) and 0.05–0.27 (ReCiPe). These plants, compared with the average comparison scenario considered, would entail an environmental impact reduction of between 15% and 55%, depending on the evaluation method used.

**Fig. 4.** Weighted environmental impact reduction for the comparison framework proposed. IMPACT 2002+.

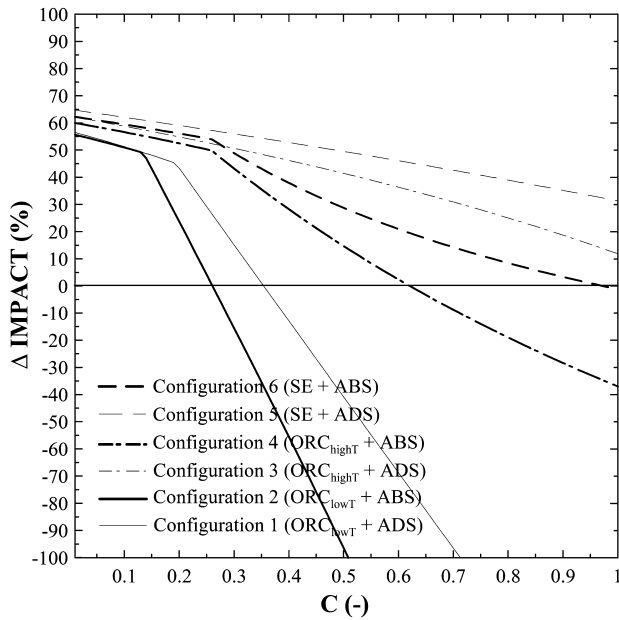


Fig. 5. Weighted environmental impact reduction for the comparison framework proposed. ReCiPe.

Despite the differences between the three LCA methods, the above-mentioned results are common to all of them. However, some other considerations might lead to contradictory conclusions when taking into account their specific results. This occurs for rather high cooling-to-heating ratio values. For example, Configuration 5 can be considered energy efficiently feasible up to a  $C$  value of 0.75, but, as can be seen in Fig. 3, the impact method Eco-Indicator 99 considers it unfeasible for, approximately, a 0.5  $C$  value, whereas the other two assessment methods do not limit the environmental feasibility within the evaluated values ( $0 \leq C \leq 1$ ).

The main differences between the LCA methods results are related to their normalization and weighting factors. For example, the relative weights of the resources depletion categories are less

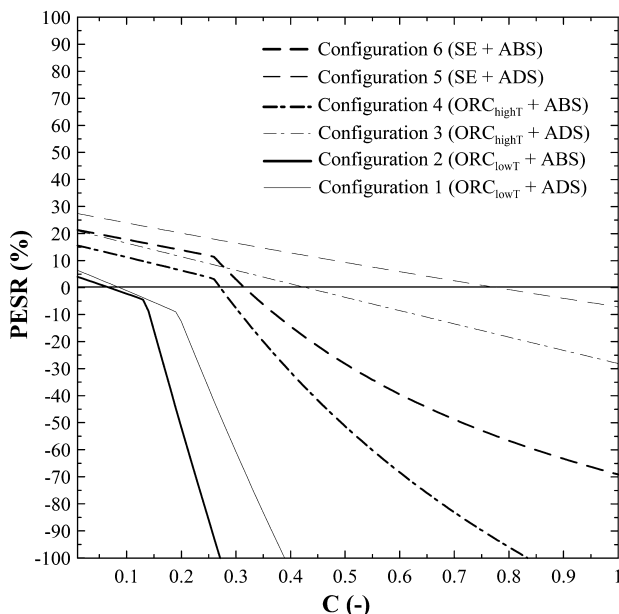


Fig. 6. Primary energy savings results for the comparison framework proposed.

important in the Eco-Indicator 99 method than in the other two which, in this specific case, condition the final relative results. For this work, the methods were selected because they allowed aggregating the impact score of every category to obtain a single result, which is enormously interesting in order to compare the environmental results with those from the energy efficiency analysis. However, the selection of the most appropriate assessment method for a certain case is one of the stages that have to be carried out before comparing alternatives if the representativeness of the results is to be guaranteed.

## 5. Conclusions

The main objectives of this work were to assess the environmental behaviour of CCHP systems based on solid biomass combustion in comparison to stand-alone conventional systems when they are integrated to supply cooling and low-grade heating demands, and to compare the results with their energy efficiency performance. In order to do so, both environmental and energy assessments were carried out, comparing six different possible bio-fuelled CCHP configurations (different technologies involved) with an average stand-alone reference system. To attain comparable results with the energy analysis and to reduce the possible subjective LCA weighting factors, three different LCA evaluation methods (Eco-Indicator 99, IMPACT 2002+ and ReCiPe) were considered.

The operation of Stirling engines and organic Rankine cycles coupled with absorption or adsorption chillers implies environmental benefits compared to conventional average stand-alone generation when the cooling loads are small in comparison to the heating ones (low  $C$  values). However, high plant cooling-to-heating ratios cause CCHP plants based on biomass combustion to be environmentally unfeasible (they do not decrease environmental impacts compared with conventional average stand-alone generation). This is the main conclusion of this work. Therefore, designers of CCHP plants based on biomass combustion must be aware of the technological and steady-state cooling and heating load constraints to avoid the operation from being environmentally unfeasible, and therefore dismissing one of the main advantages of these systems. Other considerations in the study, such as different biomass sources or a slight improvement in the PM and TAC efficiencies and coefficients of performance might affect the results, so this should also be considered in the steady-state design stage.

The secondary conclusion of this work is the difference between the results for environmental and primary energy savings (PES) performance, which should be considered by European policies to regulate and favour the operation of CCHP plants based on biomass combustion. Hence, the primary energy savings ratio should not be the only parameter used to assess the convenience of installing or granting this type of plant. Other tools, such as life cycle assessment, despite its well-known limitations, can help to draw wider conclusions about their suitability.

## Acknowledgements

This work is financially supported by the Spanish Ministry of Science and Innovation, BIO3 project ("Small-scale trigeneration based on Mediterranean energy crops and residual biomass combustion"), ref. ENE2008-03194/ALT.

## Nomenclature

|       |                                            |
|-------|--------------------------------------------|
| $C$   | cooling factor (dimensionless)             |
| $COP$ | coefficient of performance (dimensionless) |
| $F$   | fuel (kW)                                  |

|           |                                  |
|-----------|----------------------------------|
| PESR      | primary energy savings ratio (%) |
| $\dot{Q}$ | heat rate (kW)                   |
| $T$       | temperature (°C)                 |
| $W$       | power (kW)                       |

#### Greek letters

|          |                |
|----------|----------------|
| $\Delta$ | difference (–) |
| $\eta$   | efficiency (%) |

#### Subscripts

|       |                  |
|-------|------------------|
| act   | activation       |
| e     | electric         |
| highT | high temperature |
| lowT  | low temperature  |
| min   | minimum          |
| PM    | prime mover      |
| ref   | reference        |
| rej   | rejection        |
| th    | thermal          |

#### Abbreviations

|      |                                    |
|------|------------------------------------|
| ABS  | absorption cooling                 |
| ADS  | adsorption cooling                 |
| CCHP | combined cooling heating and power |
| CHP  | combined heating and power         |
| ORC  | organic Rankine cycle              |
| PES  | primary energy savings             |
| PM   | prime mover                        |
| SE   | Stirling engine                    |
| TAC  | thermally activated cooling        |

#### References

- Cardona E, Piacentino A. Cogeneration: a regulatory framework toward growth. *Energy Policy* 2005;33(16):2100–11.
- EC. Directive 2009/28/EC of the European Parliament and the Council on the promotion of the use of energy from renewable sources; 2006.
- Chicco G, Mancarella P. Trigeneration primary energy saving evaluation for energy planning and policy development. *Energy Policy* 2007;35(12):6132–44.
- Hernández-Santoroyo J, Sánchez-Cifuentes A. Trigeneration: an alternative for energy savings. *Applied Energy* 2003;76:219–27.
- Al-Sulaiman FA, Hamdullahpur F, Dincer I. Greenhouse gas emission and exergy assessments of an integrated organic Rankine cycle with a biomass combustor for combined cooling, heating and power production. *Applied Thermal Engineering* 2011;31(4):439–46.
- McKay H. Environmental, economic, social and political drivers for increasing use of woodfuel as a renewable resource in Britain. *Biomass and Bioenergy* 2006;30(4):308–15.
- MicroCHep project: the integration of micro-CHP and renewable energy systems (6th FP); 2007.
- Sunstore 4 project: innovative, multi-applicable and cost efficient hybrid solar (55%) and biomass energy (45%) large scale (district) heating system with long term heat storage and organic Rankine cycle electricity production. (7th FP); 2011.
- Jing Y-Y, Bai H, Wang J-J, Liu L. Life cycle assessment of a solar combined cooling heating and power system in different operation strategies. *Applied Energy* 2012;92(0):843–53.
- Wu DW, Wang RZ. Combined cooling, heating and power: a review. *Progress in Energy and Combustion Science* 2006;32(5–6):459–95.
- Chicco G, Mancarella P. Distributed multi-generation: a comprehensive view. *Renewable and Sustainable Energy Reviews* 2009;13(3):535–51.
- Angrisani G, Roselli C, Sasso M. Distributed microtrigeneration systems. *Progress in Energy and Combustion Science* 2012;38(4):502–21.
- Chicco G, Mancarella P. A unified model for energy and environmental performance assessment of natural gas-fueled poly-generation systems. *Energy Conversion and Management* 2008;49(8):2069–77.
- Maraver D, Sin A, Royo J, Sebastián F. Assessment of CCHP systems based on biomass combustion for small-scale applications through a review of the technology and analysis of energy efficiency parameters. *Applied Energy* 2013;102(0):1303–13.
- Pehnt M. Dynamic life cycle assessment (LCA) of renewable energy technologies. *Renewable Energy* 2006;31(1):55–71.
- Carvalho M, Serra LM, Lozano MA. Optimal synthesis of trigeneration systems subject to environmental constraints. *Energy* 2011;36(6):3779–90.
- Jing Y-Y, Bai H, Wang J-J. Multi-objective optimization design and operation strategy analysis of BHP system based on life cycle assessment. *Energy* 2012;37(1):405–16.
- Pehnt M. Environmental impacts of distributed energy systems—the case of micro cogeneration. *Environmental Science and Policy* 2008;11(1):25–37.
- Staffell I, Ingram A. Life cycle assessment of an alkaline fuel cell CHP system. *International Journal of Hydrogen Energy* 2010;35(6):2491–505.
- Caserini S, Livio S, Giugliano M, Grosso M, Rigamonti L. LCA of domestic and centralized biomass combustion: the case of Lombardy (Italy). *Biomass and Bioenergy* 2010;34(4):474–82.
- Kimming M, Sundberg C, Nordberg Å, Baký A, Bernesson S, Norén O, et al. Biomass from agriculture in small-scale combined heat and power plants – a comparative life cycle assessment. *Biomass and Bioenergy* 2011;35(4):1572–81.
- Buonocore E, Franzese PP, Ulgiati S. Assessing the environmental performance and sustainability of bioenergy production in Sweden: a life cycle assessment perspective. *Energy* 2012;37(1):69–78.
- Chevalier C, Meunier F. Environmental assessment of biogas co- or trigeneration units by life cycle analysis methodology. *Applied Thermal Engineering* 2005;25(17–18):3025–41.
- Abdul K. Exergy analysis of gas turbine trigeneration system for combined production of power heat and refrigeration. *International Journal of Refrigeration* 2009;32(3):534–45.
- Li H, Fu L, Geng K, Jiang Y. Energy utilization evaluation of CCHP systems. *Energy and Buildings* 2006;38(3):253–7.
- Directive 2004/8/EC of the European Parliament and of the Council of 11 February 2004 on the promotion of cogeneration based on a useful heat demand in the internal energy market and amending Directive 92/42/EEC. 2004.
- ISO. ISO 14040: environmental management – life cycle assessment – principles and framework; 2006.
- ISO. ISO 14044: environmental management – life cycle assessment – requirements and guidelines; 2006.
- Pré Consultants. SimaPro 7.3: life cycle assessment software; 2012.
- Frischknecht R, Rebitzer G. The ecoinvent database system: a comprehensive web-based LCA database. *Journal of Cleaner Production* 2005;13(13–14):1337–43.
- Goedkoop M, Spriensma R. The eco-indicator 99: a damage oriented method for life cycle assessment, methodology report. 2nd revised ed., vol. 4. Amersfoort (NL), Netherlands: Pré Consultants, <http://www.pre.nl/eco-indicator99/>; 2000.
- Jolliet O, Margni M, Charles R, Humbert S, Payet J, Rebitzer G, et al. IMPACT 2002+: a new life cycle impact assessment methodology. *The International Journal of Life Cycle Assessment* 2003;8(6):324–30.
- Goedkoop MJ, Heijungs R, Huijbregts M, De Schryver A, Struijs J, Van Zelm R. ReCiPe: a life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level; 2009.
- Holzenergie Bauer C. In: Dones R, editor. Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. Dübendorf, CH: Swiss Centre for Life Cycle Inventories; 2007.
- Primas A. Life cycle inventories of new CHP systems. Final report ecoinvent data v2.0, no. 20. Dübendorf, CH: Swiss Centre for Life Cycle Inventories; 2007.
- Ecoinvent. The ecoinvent database v2.0; 2009. Available from: <http://www.ecoinvent.org/documentation/reports/>.
- Dones R, Bauer C, Bolliger R, Burger B, Faist Emmenegger M, Frischknecht R, et al. Life cycle inventories of energy systems: results for current systems in Switzerland and other UCTE countries. Final report ecoinvent data v2.0, no. 5. Dübendorf, CH: Swiss Centre for Life Cycle Inventories; 2007. Available from: <http://www.ecoinvent.org/documentation/reports/>.
- EC. Directorate-general for energy. Europe's energy position: 2010 annual report; 2011. Available from: <https://infoeuropa.eu/ocid.pt/files/database/000047001-000048000/000047063.pdf>.
- Cardona E, Piacentino A. A methodology for sizing a trigeneration plant in mediterranean areas. *Applied Thermal Engineering* 2003;23:1665–80.
- Commission implementing decision of 19 December 2011 establishing harmonised efficiency reference values for separate production of electricity and heat in application of Directive 2004/8/EC of the European Parliament and of the Council and repealing Commission Decision 2007/74/EC; 2011.
- Obernberger I, Carlsen H, Biedermann F. State-of-the-art and future developments regarding small-scale biomass CHP systems with a special focus on ORC and Stirling engine technologies. In: International Nordic bioenergy conference: BIOS BIOENERGIESYSTEME GmbH; 2003.